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A 2D typology generator for historical masonry elements

Shenghan Zhang, Martin Hofmann, Katrin Beyer *

Earthquake Engineering and Structural Dynamics (EESD), Institute of Civil Engineering, ENAC, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

HIGHLIGHTS

- A new typology generator for historical stone masonry is presented.
- Source code and parameters for typical typologies of the Italian code are provided.
- A generalized definition for the line of minimum trace is proposed.
- An algorithm for calculating the line of minimum trace is presented.
- Masonry compressive strength is positively correlated with line of minimum trace.

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ABSTRACT

The mechanical response of stone masonry depends on the properties of the components and also on the typology created by the stone units and the mortar joints. While the influence of the component strength on masonry is relatively well studied, few studies have been devoted to its influence on masonry properties mainly because of the difficulty of varying the masonry typology systematically. This paper focuses on generation and calibration of masonry typologies, which serves as foundation for further numerical investigation. To this purpose, we develop a typology generator based on relevant research in computer vision. To characterize different typologies quantitatively, we also develop an objective method to compute the line of minimum trace directly from the image of stone masonry based on graph theory. The code and recommendations for the parameter choices are publicly available online. Altogether, this paper provides a useful tool for researchers to study systematically the influence of historical stone masonry typologies.

1. Introduction

Stone masonry is one of the oldest construction materials and can be found in many of today's cultural heritage structures. Stone masonry buildings are also among the most vulnerable structures under earthquake loading [1,2] and other disasters. Effectively planning strengthening interventions requires a good understanding of their seismic behavior [3]. However, understanding the mechanical behavior of stone masonry elements is a long-standing challenge in civil engineering [4].

One traditional way in this field is to focus on a certain type of masonry [5,6] and to obtain global strength values or deformation capacities through a series of experimental tests. Although useful engineering indices can be obtained in this way, the substantial variety of masonry and the difficulty of controlling certain parameters in experiments (e.g. stone shape, stone size distribution, distribution of material properties within the element) make it impossible to exhaust all typologies. Thus a deeper understanding of the material is required.

The mechanical response of stone masonry is determined by the properties of the components and also dependent on the typology created by the stone units and the mortar joints. There have been already some studies on the influence of the component strength on masonry properties [7,8]. Research on the influence of the typology on the masonry properties is, however, relatively scarce. One of these studies is the pioneering work on interlocking by Mann and Müller [9]. Recent developments along this line include the work by Calderini et al. [10,11]. However, these studies concentrated only on regular masonry (e.g., brick masonry) for which the generation and the quantification of the typology are much simpler than for irregular stone masonry. The same limitation also exists for various homogenization methods [12] where a representative

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* Corresponding author.
E-mail address: katrin.beyer@epfl.ch (K. Beyer).

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volume element is based on brick masonry for which the typology is easy to define.

Two major obstacles that hinder related research on historical stone masonry are the difficulties of systematically generating and accurately quantifying patterns for different typologies. Due to these limitations, in previous research, e.g., [13,14], typologies were only compared and differentiated qualitatively. Recently, the concept of the line of minimum trace (LMT) [15,11,16] has been put forward to quantitatively characterize the masonry typology. However, in these works the line of minimum trace is evaluated manually, which is time-consuming and can even lead to subjective results if possible paths are discarded due to misjudgment.

To address the two obstacles above, this paper is devoted to complement existing research on stone masonry by developing the first generator for stone masonry typologies and by developing a tool for calculating the LMT automatically. These two contributions will allow to conduct systematic numerical studies on the effect of stone masonry typologies on the resulting element strength and deformation properties and will also benefit other research objectives that are based on the micro-structure, e.g., the development of homogenization and multi-scale modeling methods for stone masonry.

The structure of the paper is as follows: Section 2 of this paper introduces the stone masonry typologies that are typically distinguished and which we aim to generate using our micro-structure simulator. In Section 3, we describe the typology generator. This part of research is based on related research in computer vision [17]. In order to represent real masonry typologies, important improvements are introduced, including the implementation of the erosion process generating mortar layers of varying thickness and the Voronoi splitting of certain regions [18,19] in order to obtain more irregular patterns. Section 4 introduces the algorithm for computing the LMT. To automate the process, we reformulate the problem as a shortest path problem in graph theory [20] and use the classical Dijkstra's algorithm [21] to calculate the LMT. In reality, cracks tend to follow the mortar-stone interfaces because interfaces are normally weaker than the mortar itself. In order to consider this physical reality, we further generalize the definition of the LMT by assigning different weights to the interface and the mortar. Section 5 presents the application of the typology generator and a comparison with reference patterns. To illustrate how the typology generator can be used with the detailed micro-modeling method, we transform the patterns into finite element meshes and analyze the compressive strength of the generated samples.

2. Classification of stone masonry typologies

Today, masonry typologies are classified by comparing their pattern visually to example patterns in design codes. Typically, five classes are distinguished (a definition of these classes can be found in Table C8A.2.1 [22]; the various typologies are shown in Fig. 1 taken from [6]):

- Class A: irregular stone masonry, with pebbles, irregular stone units;
- Class B: uncut stone masonry;
- Class C: cut stone masonry with good bonds;
- Class D: soft stone regular masonry (built with tuff or sandstone blocks);
- Class E: Ashlar masonry, built with sufficiently resistant blocks.

As a sixth class, we introduce block (Ashlar) masonry, where the blocks are perfectly rectangular and all blocks of one row have the same height. This typology covers cut stone (Ashlar) masonry as well as modern brick masonry, where all blocks have the same size.

A first step towards a non-discrete classification system is the Masonry Quality Index (MQI) developed by Borri et al. [23] based on a procedure by Binda et al. [24] for assessing the quality of stone masonry and its compliance to the "rules of the art" [24,25]. It accounts for the mechanical properties of the constituents, the

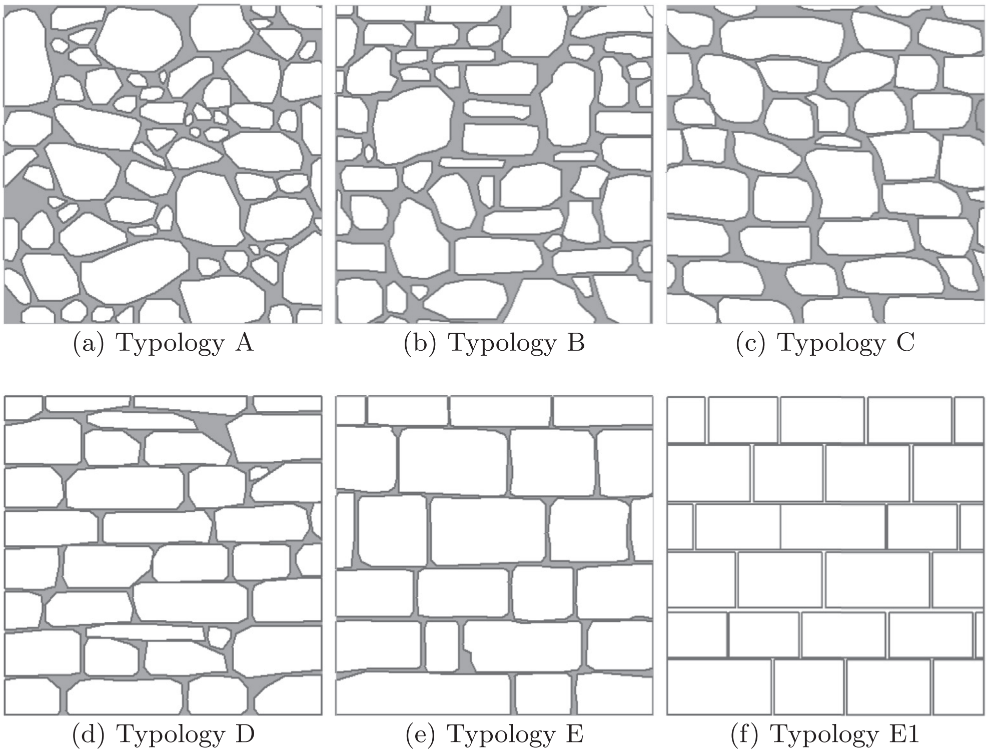
(a) Typology A (b) Typology B (c) Typology C
(d) Typology D (e) Typology E (f) Typology E1

Fig. 1. Patterns of five stone masonry typologies that are defined by the Italian code [22] and a block masonry pattern. Sketches from Vanin et al. [6].